INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS

2016 EDITION

ENVIRONMENT, SAFETY, AND HEALTH

WHITE PAPER

ENVIRONMENT, SAFETY AND HEALTH

1. CHARTER AND MISSION

Our IRDS Environmental, Safety and Health Charter and Mission are described here, in summary with our ESH Working Group "Fifteen Core Strategies". These strategies are extensions and improvements of the strategies used in the Semiconductor and Electronics Industries for several decades. Here they have been adopted for Devices and Systems, from previous specific industry roadmap entities, constructed and proved useful during 20+ years of Semiconductor Roadmapping. They are broadened and extended for the fuller context of the International Roadmap for Devices and Systems, specifically in regards to the full range of technology applications and devices envisioned in the time horizon to 2030.

- Define a long term, and broad vision for the semiconductor industry, including technical direction, key gaps and opportunities in ESH (and sustainability)
- Build a framework process and flexible vehicle for ongoing collaboration by key all key stakeholders globally (aligning with adjacent industry sectors: ACS, ACC, INEMI, MEMS, Sensors, etc).
- A mechanism for tying long range technical challenges to medium range technology development, to address near term challenges (regulatory landscape is the foundation for forward looking direction, as the goal is to design out the issues up front, not react to them).
- Key emphasis: to enable more effective decision making, emphasize a systems integration approach to problem solving and to address risk mitigation, as well as forward looking opportunities for the industry to perform 'for the environment, in the application of the strategies, systems, processes and devices developed by the industry, to apply to broader ESH challenges globally.
- Emphasize strategies that drive proactive engagement in the ESH space:
    - Cross disciplinary and organizational collaboration : to provide proactive engagement with stakeholder partners and customers and reset strategic focus on the roadmap goals
    - Design for environment: process, products and systems (equipment and facilities) that consume less raw materials and resources, to understand and characterize these with a long term, life cycle perspective
    - Green chemistry and engineering, use of alternative assessment methodologies:
        - Promoting materials, equipment and process development design, that comprehend ESH long term considerations, as part of the decision making process across the entire technology life cycle.
- Understand and coordinate a forward looking process and strategy, which comprehends emerging regulations, rules and policies, to accurately capture the regulatory landscape, to enable effective technical strategies and to address these issues in advance.
- Proactively comprehend emerging materials (such as new metals and resists), as well as equipment challenges, emphasizing a collaborative, pre-competitive approach.
- To provide a clear global ESH perspective with regards to the introduction of new materials, and green chemistries used for making Systems and Devices. To roadmap, insofar as possible, impacts in measurable and quantitative ways. To provide forward-looking visibility of the key aspects to 2030.
- To collaborate with appropriate key stakeholders and contribute to developing descriptions of the full life cycle ESH outcomes and the full cycle costs assocated with the introduction of new products and processes. To understand (characterize) processes and materials through the earlier pathfinding and early development hases, in order to better construct quantitative forward-looking roadmaps for the

entire life of the technology operatng inside the devices and systems envisioned within the time horizon.

- To encourage the industrial use of materials that are less hazardous and whose byproducts are less hazardous;
- To provide useful and helpful baseline information for the design of devices and systems (using equipment, materials and facilities) that consume less raw materials and use resources more efficiently and sustainably (eco-efficiency);
- To help describe manufacturing process optimization and minimize waste generation and/or to increase recycling and re-use rates. Early quantification of energy use, water consumption, and waste generation has been completed, the roadmap will continue in the goal of quantifying use further for more critical materials and additional facility parameters in the time horizon to 2030.
- To provide proactive continuous engagement with stakeholder partners throughout the industry and help to reset strategic focus on the quantitative roadmap ESH goals
- To assist the predictions of impact of new codes and regulations on chemical use and waste discharge and to collaborate on strategies and potential solutions.
- Fully comprehend Nanotechnology Standards through broader global collaboration

By applying these Fifteen Core Strategies as the basis of our activities and formalizing them into our Charter, the ESH Working Group will feed inputs to Factory Integration Focus Group and other functional groups in order to help the electronics industry to continue to be an ESH global leader as well as maintain its position as a technology leader.

The misson of the IRDS ESH Working Group is to help and assist in all of the working processes and aspects to ensure that the electronics/computer/systems industry manufactures its products in the safest and most sustainable manner, given the complex existing regulatory and economic environment. This will be achieved through proactive continuous engagement with relavent institutional, governmental, regulatory and industrial stakeholders to develop the information and the processes required so that ESH related life cycle costs can be considered early in the equipment and processs development cycles. The ESH Working Group has quantified energy use, water consumption and waste generation reduction goals, and is focusing on quantifying further the critical materials usage in our industry.

2. Scope

The Environmental Safety and Health (ESH) Working Group projects the principles of a successful, sustainable, long range, global, industry-wide ESH program. Execution remains largely independent of the specific technology thrust advances to which the principles are applied. Thus, many ESH Roadmap elements, such as the Difficult Challenges and the Technology Requirements, remain similar to those presented in earlier Roadmaps. Notice that we do keep a difficult challenges table. (see below)

Historically the ESH Work Group we managed the ESH process through a well-defined set of six fully developed, quantitative tables and charts. In IRDS 2016 we have reviewed and are updating the ESH metrics and graphics to improve data linkages to much broader data sets, for a wider range of systems, applications and devices. Accordingly our scope has increased beyond the scale of our historic ITRS semiconductor origins and going forwards will consist of eight charts. The ESH roadmap identifies challenges when new system manufacturing, wafer processing and A&P technologies move through research and development phases, and towards manufacturing insertion. Following the presentation of ESH Domains and Categories, ESH technology requirements are fully listed in another table (not shorn here). A greater focus has been placed on Sustainability and Green Chemistry as shown in further tables. Potential technology and management solutions to meet these challenges are proposed. Successful resolution of these challenges will best be realized when ESH concerns are integral in the thinking and actions of process, equipment, and facilities engineers; chemical/material and tool suppliers; and academic and consortia researchers. ESH improvements must also support (or at minimum, not conflict with) enhanced technical performance, product timing, and cost-effectiveness. Further, ESH improvements must inherently minimize risk, public and employee health and safety effects, and environmental impact. For this purpose we have introduced (as shown in figure below)o a methodology to explain the necessary processes for consensus building of stakeholders to ensure full lifecycle risk assessment. Successful global ESH initiatives must be timely, yet far reaching, to ensure long-term success of the entire Semiconductor Technology Roadmap**.**

Significant increases in scope since the last ESH Semiconductor Whitepaper publication includes specific new packaging and technologies such as:

- Photonics and it's integraton in the packaging aspects of devices.
- MTM and beyond CMOS applications such as power devices in SiC and GaN, sensors and advanced communications requirements.
- Internet of Things devices including bio-based sensors.

3. Cross Team Interactions

The ESH Working Group interacts with ALL other working groups and Focus Areas of IRDS. Clearly there are specifically strong interations in Emerging Materias, Facilities, Factory Integration, Lithography and Front End processing. Some will be summaried below.

4. Stakeholders

ESH is impacted in all that we do as an industry in Systems, Devices and the entire lifecycle of devices and systems. In terms of Stakeholders Internal to the IRDS Roadmap as the ESH Working Group we are mosted connected with the following Eight Categories. A large part of what we do is extensive open communication with a very wide range of globally colaborating stakeholders:

1. Internal IRDS Roadmap: Roadmap Management, Factory Integration, Metrology, Device and Assembly/Packaging, Lithography, ERM, FEP. Emerging new structures under IEEE guidance.
2. Semiconductor Industry: associations (WSC, SIA, JEITA, KSIA, TSIA, ESIA), and WSC (policy), SEMI
3. Research consortia: iMEC, ITRI, Fraunhofer, Leti and SRC/ERC, CNSE, Tyndall
4. Adjacent industry (technology life cycle): ACC, ACS/GCI, INEMI, MEMS, Sensors
5. Government Agencies: OCED? ECCA, US EPA, NIST
6. Regional Co-ordinators: IEEE, NEREID, SDRJ, (China Ministry of Technology?), (Korea?)
7. Industry Associations, primarily: WSC, SIA, JEITA, KSIA, TSIA, ESIA,WSC (policy), SEMI, iNEMI

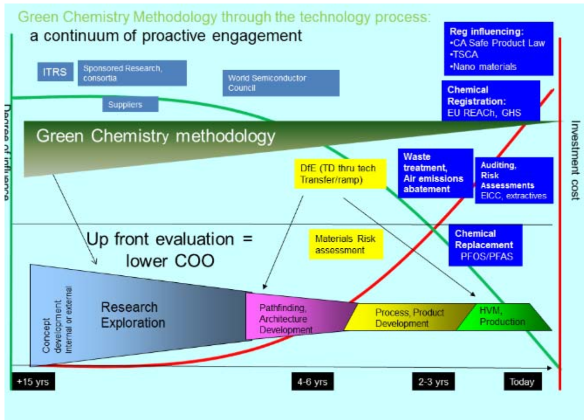
Our significant stakeholders for the ESH Working group include all the active stakeholders for the Factory Integration Group include all solution manufacturers and suppliers and that covers all manufacturing sectors including front-end, back-end, facilities and linkage to the upstream and downstream supply chain. Stakeholders also include *all* device designers especially from the perspective of the the tighter linkage between design and manufacturing via design for manufacturability innovations and the increased use of cyber-physical systems. Within the IRDS, the ESH has strong cross-TWG linkage to FEP, Packaging, YE, Lithography, Metrology, Test, ERM and Design. Stakeholders also include local communities wherever semiconductor manufacturing operation takes place, and the related government groups associated with manufacturing. One major issue with ESH in IRDS is the vast breadth of interactions. This is a major challenge in itself.

5. Technology Status, New Requrements and Potential solutions

The practices of ESH are well established in the Semicoductor Industry. The requirements are well-documented elsewhere. In this IRDS Work Group we take a Proactive Look Outside of CMOS. MTM, IoT, Sensors, Heterogeneous, Photonics, Biochips, RF, Power, not to say they were not previously comprehended, but now requiring a deeper comprehension and further quantitative analysis. This process includes organics, polymers, nanoparticles, in terms of new materials.

5.1. Technology Status and Update

Green Chemistry - Key Emerging Program: Through the last few iterations of the ESH section of the technology roadmap, the authors have introduced the concepts of Green Chemistry, as developed by Anastas and Warner, in their seminal 1998 book. Though written from a synthetic chemistry perspective, the core 12 principles delineated there are relevant and vital to any industry sector, though the relative importance of each may vary based on the application. However, while Green Chemistry has been integrated qualitatively into the roadmap and experienced some measure of adoption by semiconductor manufacturers and suppliers, much work needs to be done in achieving widespread integration and implementation across the industry. Given the volume, sources and complexity of regulation, materials availability and downstream implications, as well as diversity of products and supply chain, the need for a long term (life cycle) approach that proactively develops and drives technical solutions which address EHS challenges up front is a critical necessity. The roadmap provides an ideal framework for taking a long view on technology development, employing the requisite systems integration approach that is vital in creating comprehensive solutions and processes for the industry in the future. Applying Green Chemistry concepts and tools across the technology life cycle, from materials and equipment research through development to ongoing manufacturing, and providing the appropropriate tools (i.e. alternative assessment methologies to drive materials replacements) and systems at each key decision point along the way, is the only viable path forward in addressing EHS challenges. Reacting to existing regulations is simply no longer possible, given the R&D time required in the development of new technologies. The focus going forward for the roadmap, will be setting goals and direction for driving widespread understanding and awareness for green chemistry, and a path toward the development of tangible implementation strategies across the technology lifecycle (Ref. 1)



Lithography: ESH continues working on the sustainability aspects of New Lithography, new mask, new lasers, safety energy etc in EUV adoption. Light Source Efficiency. Introduction of EUV exposure has major fab impacts in terms of power and water usage. Examination of the Full litho supply chain, including new resist chemistries is underway.. The adoption of EUV is expected to significantly increase the energy consumption of a given wafer fab. Since the EUV tools are still in the early stages of development, it is unclear what their average power consumption will be and what wafer throughput each tool will provide. The power consumption roadmap is based on the following assumptions;

- EUV tools are starting to be utilized in in HVMs in 2016 and 2017
- Each EUV tool uses on average 810 kwatts (and up to to 1MW, in the most recent configuration)
- The throughput of the EUV tools is 20% that of 248/193nm scanners (single pass) and this is rising to 50%. But electrical power and cooling water will also increase.
- The assumption of number of mask levels that use the EUV tool starts at 2 and increases over time is being calculated fully into the model.

While much of the responsibility for resource reduction and waste minimization rests with equipment suppliers and process technologists, applying advanced resource management programs to factory systems will have a significant impact as well. These future programs' goal is to build factories that minimize resource consumption and maximize the reuse, recycle, or reclaim of by-products. Key factory-related ESH programs require water reuse in process and non-process applications, energy efficient facilities equipment, improved facilities system design, and new facilities operating strategies.

In this Whote Paper we have detailed two key areas. In the entire ESH work there are too many to describe here. Inclusion of consideration of Industry 4.0, and Big Data in the ESH analyses is now required and this will also be reported in 2017. (Ref. 2,3)

5.2. Specific New Requirements & Difficult Challenges

The ESH roadmap identifies many challenges occurring, initially when new wafer processing and A&P technologies move through research and development phases, and towards manufacturing insertion.. Potential technology and management solutions to meet these challenges are now proposed.. Successful resolution of these challenges will best be realized when ESH concerns are integral in the thinking and actions of process, equipment, and facilities engineers; chemical/material and tool suppliers; and academic and consortia researchers. ESH improvements must also support (or at minimum, not conflict with) enhanced technical performance, product timing, and cost-effectiveness. Further, ESH improvements must inherently minimize risk, public and employee health and safety effects, and environmental impact. Some specific Challenges being worked upon include:

- Rework quantitative calculations for water based on 2016 inputs
- Spray cleaning delivers all particles to wafer, so achieving defects is the deciding factor
- F-GHG reduction is defined by WSC, but we keep this target in the tables
- For ESH, new restrictions of use from EPA sometimes appear for existing materials; we consider this not to be a roadmap issue.
- We use Green Chemistry Principle for bringing on ALL New Materials
- No changes in toxic wastes, total waste or CFC
- Need to analyze VOC (volatile organic compounds) increasing solvent use in assembly. Include assembly in analysis and assessment as they can be major potential sources
- Compare Water consumption, Energy use, CFC Metrics, fab level to mass level calculations
- Nanomaterials require a new section in the roadmap
- New elements and precursors
- Add additional metrology and more data with specific cases
- New Energetic materialss
- Green Chemistry
- New Litho, new mask, new lasers, safety energy etc in EUV adoption. Light Source Efficiency.
- Full litho supply chain.
- Eco and resource efficiency, water, hydrogen, overall facilities etc.
- Industry 4.0

5.3. FUTURE CHALLENGES

The following table captures challenges and the details and status of the issues

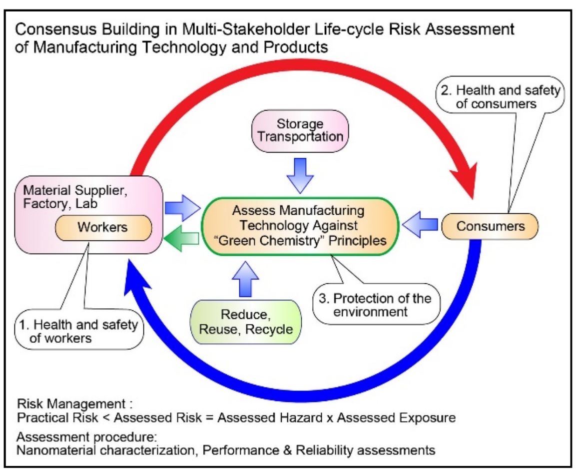
Challenges	Category	Short description	Comments
Nanomaterials	New materials	Significantly broader elemental range of emerging materials and their compound	First introduction in Assembly and Packaging: TSV, Filler materials, etc.
Energetic materials	New materials	ESH Impact	
Introduction of energetic materials	New materials	ESH Impact, such as Organometals, Safety issues at interfaces between	

		supply/process and effluent treatment, e.g. supply of liquid materials	
III/V materials	New materials	ESH Impact, e.g. AsH3 outgassing (e.g. during cleaning)	
Availability of materials	New materials	Availability, reuse and recycling	e.g. Xe
Fab energy and water usage	Resources	Energy and water availability	Continuous effort, Regulations are introduced step by step
Water recycling in fabs	Resources	Trends in water recycling based on segregation	Costs is high and therefore an obstancle, need for affordable solutions
EUV lithography	Resources	Energy and utility consumptions	Major challenge
Expanded use of single wafer cleans	Resources	Increase in chemical and water consumption instead of reduction, insufficient segregation	Still a concern
450mm wafer processing	Resources	Energy and utility consumptions	
Power monitoring	Metrology	Methodologies and instrumentation: More engineering efforts to monitor and optimize tool power usage needed	
Continuously effluent monitoring	Metrology	Methodologies and instrumentation	
Materials risk assessment and selection	Process development	General, material selection roadmap, Sustainability and Green Chemistry, avoidance of secondary costs, conflict materials	
Molecular efficiency (e.g. ALD)	Process development	Effluents, material conversion efficiency	
Ensure Full Lifecycle Risk Assessment, exposure risk	General	Evaluate risks and carbon footprint, standardized model, data	Combine with material risk assessment
# of regulations	General	Rapidly increasing numbers provides challenge for compliance	

Sustainability	General	Methodologies: selection of KPI, reports to what standards	
Air emissions	Regulations	Requirements for VOC, NOx etc & testing methods require improvements	
GHG emissions	Regulations	Regulatory requirements F-GHG, N2O	
Materials regulations	Regulations	Regulatory requirements, e.g. ban on PFOS, PFOA; PFAS etc. in articles	
TMAH	Regulations	Regulatory requirements for concentrated chemicals	
CE certified equipment	Tools	Costs for small innovative companies for compliance certification	

6. SUMMARY

Significant new challenges are being faced in Systems and Device Manufacture with respect to ESH. The increasing number and complexity of chemical regulations around the globe, coupled with adding many new materials into emerging devices, results in major ESH Challenges. This is further exacerbated by EUV and single wafer cleaning processes with significantly greater energy use and water consumption per wafer. Rigorous quantitative models have been built to address these aspects. We seek, generally, to better quantify all ESH activities. These challenges have been described in this chapter. A deeper process of consensus building from a larger range of stakeholders has been implemented to provide full lifecycle risk assessment as shown below.



Successful resolution of these challenges will best be realized when ESH concerns are integral in all the thinking and actions of process, equipment, and facilities engineers; chemical/material and tool suppliers; and academic and consortia researchers. ESH improvements must also support (or at minimum, not conflict with) enhanced technical performance, product timing, and cost-effectiveness. Further, ESH improvements must inherently minimize risk, public and employee health and safety effects, and environmental impact. For this purpose a new Figure ESH2 has been added to explain the necessary processes for Consensus Building of Stakeholders to Ensure Full Lifecycle Risk Assessment. Successful global ESH initiatives must be timely, yet far reaching, to ensure long-term success of the entire Semiconductor Technology Roadmap. Accordingly a new Challenges table has been assembled.

As we need move to a new era for the devices and systems roadmap with the the transitional alignment to IEEE, this association reflects the broader, more expansive implications of today's technology landscape and the complex interrelationships across the life cycle of devices and systems. Despite this broader view of the roadmap, the critical importance of the core mission and work in the semiconductor industry remains, as the fundamental industry segment where proactive integration of technical solutions can most effectively address EHS challenges, with advances in materials, equipment and process development.

Therefore, this reset represents a significant paradigm shift in the role of the semiconductor technology roadmap for ESH, as a focal point for a broader effort among all key stakeholders, as collaborative process, taking a long range and systems integration approach to solving these expansive challenges. Starting with the traditional roadmap core competencies of identifying challenges for wafer processing and Assembly & Packaging, through research and development to manufacturing (Table 1), the key technical gaps and opportunities for the industry are highlighted to provide guidance on where to focus going forward. Following the presentation of ESH Domains and Categories in Table ESH2, ESH technology requirements are listed in Tables ESH3–5. A greater focus has been placed on Sustainability and Green Chemistry in Tables ESH4-5. Potential technology and management solutions to meet these challenges are proposed in Figure ESH1. Further quantitative analyses of new metrics will be presented in several more tables. Successful resolution of these challenges will best be realized when ESH concerns are integral in the thinking and actions of process, equipment, and facilities engineers; chemical/material and tool suppliers; and academic and consortia researchers. ESH improvements must also support (or at minimum, not conflict with) enhanced technical performance, product timing, and cost-effectiveness. Further, ESH improvements must inherently minimize risk, public and employee health and safety effects, and environmental impact. For this purpose a new Figure ESH2 has been added to explain the necessary processes for Consensus Building of Stakeholders to Ensure Full Lifecycle Risk Assessment. Successful global ESH initiatives must be timely, yet far reaching, to ensure long-term success of the entire Semiconductor Technology Roadmap. Accordingly a new Challenges table has been assembled with defined owners for each item.

Ultimately, the ongoing success of the roadmap, will depend on the active engagement of all key stakeholders, in how we address EHS challenges, from equipment and materials research, through process development and device fabrication, transitioning into the electronics industry and end of life. Going forward, the sustainability and impacts of use, as well as the value of how novel devices can work 'for the environment', and how to design out waste through the lifecycle, represent the new frontiers in these areas.

7. REFERENCES

[1] Paul Anastos and John Warner, "Green Chemistry: Theory and Practice," Oxford University Press, USA, 1998

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[3] INDUSTRIE 4.0 – Smart Manufacturing for the Future (Germany Trade & Investment, http://www.gtai.de/GTAI/Content/EN/Invest/_SharedDocs/Downloads/GTAI/Brochures/Industries/industrie4.0-smart-manufacturing-for-the-future-en.pdf)

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